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Enabling Temporal Observations of Cloud and Precipitation Processes using Small Satellites: TEMPEST-D Demonstration on a CubeSat for 3 Years and Follow-on Missions

Steven C. Reising[1], Chandra V. Chandrasekar[1], Shannon T. Brown[2], Wesley Berg[3], Christian D. Kummerow[3], Todd C. Gaier[2], Sharmila Padmanabhan[2], and Chandrasekar Radhakrishnan[1]
[1]Colorado State University, Electrical and Computer Engineering, Fort Collins, CO, United States of America (steven.reising@colostate.edu)
[2]NASA/Caltech Jet Propulsion Laboratory, Pasadena, CA, United States of America (shannon.t.brown@jpl.nasa.gov)
[3]Colorado State University, Atmospheric Science Dept., Fort Collins, CO, United States of America (kummerow@atmos.colostate.edu)

Temporal Experiment for Storms and Tropical Systems – Demonstration (TEMPEST-D) is a nearly 3-year NASA mission to demonstrate global observations from a multi-frequency microwave sensor deployed on a 6U CubeSat platform. TEMPEST was proposed to Earth Venture Instrument-2 in 2013 to perform high temporal resolution observations of rapidly evolving storms using a constellation of five 6U CubeSats with identical microwave sensors in a single orbital plane, providing 7-minute temporal sampling of rapidly-developing convective activity over 30 minutes. To demonstrate necessary capability for TEMPEST constellation operation, NASA's Earth Venture Technology program funded the TEMPEST-D mission, a multi-frequency microwave radiometer on a single 6U CubeSat, successfully delivered for launch less than 2 years after PDR.

TEMPEST-D was deployed from the ISS into low Earth orbit on July 13, 2018, and observed the Earth's atmosphere nearly continuously until it re-entered on June 21, 2021. TEMPEST-D performed the first global Earth observations from a multi-frequency microwave radiometer on a CubeSat. The TEMPEST-D mission substantially exceeded expectations of data quality, stability, consistency and mission duration. TEMPEST-D data were validated using the double-difference technique for cross-calibration with scientific and operational microwave sensors observing at similar frequencies, including 4 MHS sensors on NOAA-19, MetOp-A, -B and -C, as well as GPM/GMI. These validation results showed that TEMPEST had comparable or better performance to much larger operational sensors in terms of calibration accuracy, precision and stability throughout the nearly 3-year mission.

TEMPEST-D performed detailed observations of the microphysics of hurricanes, typhoons and tropical cyclones during three consecutive hurricane seasons. Simultaneous observations by TEMPEST-D and JPL's RainCube weather radar demonstrated physical consistency and well-correlated passive and active microwave measurements of severe weather from the two CubeSats. Quantitative precipitation estimates retrieved from TEMPEST-D data are highly

correlated with standard ground radar precipitation products, such as NOAA/NWS MRMS. TEMPEST-D also periodically performed along-track scanning measurements to provide the first space-borne demonstration of “hyperspectral” microwave sounding observations to retrieve the height of the planetary boundary layer.

The stability, accuracy and reliability of TEMPEST-D on a 6U CubeSat open a breadth of possibilities for future Earth observation and science missions on small satellites to enable rapid temporal observations of cloud and precipitation processes. Early in the development of the TEMPEST-D mission, a nearly identical microwave sensor, TEMPEST-D2, was produced alongside the original to reduce risk from the original manifest for launch. TEMPEST-D2 was delivered to the U.S. Space Force in 2021 for integration with the Compact Ocean Wind Vector Radiometer (COWVR), previously developed by NASA/Caltech JPL. On December 21, 2021, COWVR and TEMPEST-D2 were launched from KSC as part of the Space Test Program (STP-H8) mission for at least 3 years of operations on the ISS. These two passive microwave sensors provide a unique, synergistic opportunity for coordinated global observations of the Earth’s oceans and atmosphere using complementary small satellite instruments. Finally, the demonstrated success of TEMPEST-D and RainCube was essential in NASA’s selection in November 2021 of the Investigation of Convective Updrafts (INCUS) mission as Earth Venture Mission-3, to be launched in 2027.